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TECHNICAL REPORT BRL-TR-3227

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BRLCB: A CLOSED CHAMBER DATA ANALYSIS PROGRAM WITH PROVISIONS FOR DETERRED AND LAYERED PROPELLANTS

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APRIL 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

91 5 08 060

NOTICES

UNCLASSIFIED

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 1991

3. REPORT TYPE AND DATES COVERED
Final, Jul 87 - Dec 88

4. TITLE AND SUBTITLE
BRLCB: A Closed Chamber Data Analysis Program With Provisions for Deterred and Layered Propellants

5. FUNDING NUMBERS
DA311880
1F2Z9W
9XDGS3

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
BRL-TR-3227

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

BRLCB is a PC-based data analysis program designed to perform all data analysis associated with closed chamber experiments. Included in the program are provisions for deterred and layered propellants as well as homogeneous propellants. The basic features of the program are presented and validated, and future plans and additions to the program are outlined.

14. SUBJECT TERMS
closed bomb; closed chamber; deterred propellant; burning rate; propellants

15. NUMBER OF PAGES
30

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

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1. INTRODUCTION

One of the primary missions of the Interior Ballistics Division (IBD) of the Ballistic Research Laboratory (BRL) is the design, testing and evaluation of proposed gun propulsion systems. A key element of this mission is the accurate characterization of the combustion properties of the propelling charge. Thermochemical properties of the propellant, impetus, etc., can be determined through the use of the thermodynamic equilibrium computer programs such as BLAKE (Freedman 1982). However, the effect that a proposed propellant formulation will exert on the propellant's burning surface regression rate or surface area progressivity can only be empirically determined by closed chamber or strand burner experimentation and analysis.

In order to provide the necessary expertise for propellant analysis during the past decade, BRL has been engaged in the development and expansion of its high pressure combustion diagnostic facility. This has resulted in the acquisition and/or fabrication of closed chambers and pressure transducers capable of dealing with pressures up to 1,400 MPa, optically transparent chambers allowing visual observation of propellant combustion to 400 MPa, and interrupted chambers (blow-out bombs) which can accommodate loading densities (grams of propellant/chamber volume in cm^3) approaching those used in actual gun firings. Besides hardware, the improvements to the diagnostic facility include the development of several flexible closed and/or interrupted chamber data analysis computer programs. The most current and comprehensive of these programs is BRLCB.

The objective of this paper is to overview the major features of the BRLCB code, assess its accuracy in determining burn rate or surface area information from closed chamber pressure-time data, and outline proposed modifications and extensions to the program.

2. MAJOR FEATURES

The philosophy underlying the development of BRLCB is to provide a flexible PC-based computer program capable of performing all data analysis associated with the high pressure combustion diagnostic facility while at the same time focusing on the user interface. Whenever possible, the program is written to offer the user options through the use of self-

explanatory menus. Extensive error trapping is employed to reduce the frustration associated with premature program termination due to data input errors. In addition, the user is generally allowed to preview data which has just been entered to permit corrections before proceeding. The intent of the program is to allow for effective use by the novice as well as the experienced user.

The following list shows the main menu for BRLCB which is used to select from the twelve main options available with the program. In the remainder of this section, the major options of the program will be briefly described.

1. Create Master Information File
2. Update Gage Information File
3. Import Voltage/Time Data
4. Convert V/t Data to P/t Data
5. Analyze P/t Data (FFT, etc.)
6. Enter Firing/Reduction Data
7. Smooth/Differentiate P/t Data
8. Burn Rate Analysis
9. Surface Area Analysis
10. Synthetic Mode Analysis
11. Interrupted Chamber Analysis
12. Prepare Output
13. Exit Program

2.1 <u>Create Master Information File</u>. Generally, closed chamber experiments consist of a series of firings where the majority of the data required to perform the data analysis remain fixed from one firing to the next. This option is used to create a file containing the data which do not change during the series of firings. The data items requested include identification information pertaining to the propellant source and lot together with a complete description of the thermochemical and topological properties of the propellant. To accommodate layered and deterred propellants, propellant properties can be specified for up to ten homogeneous layers for certain grain geometries. Finally, to minimize propellant form function mismatch between the experiment and data analysis, inconsistencies in the entered grain dimensions are identified and automatically rectified upon user approval.

2.2 <u>Update Gage Information File</u>. At BRL, closed chamber pressure-time history is recorded by the use of a Kistler model 607C3 or C4 pressure transducer, Kistler model 504E or 5004 charge amplifier, and Nicolet digital oscilloscope. Actual recorded data are in units of voltage and time, which must be converted to engineering units of pressure and time. This

conversion is done by a second-degree polynomial, which converts voltage to pressure based upon conversion factors obtained through gage calibration performed at BRL. The purpose of the gage information file is to maintain a history of a gage's calibration and to minimize user error associated with entering conversion factors. This file is automatically accessed and read in option 4, which converts the voltage data to pressure data.

2.3 Import Voltage/Time Data. As mentioned above, experimental data are recorded via a Nicolet digital oscilloscope. The diskette format of the Nicolet is not compatible with that of the IBM. Thus, the purpose of this option is to transfer voltage-time data from the Nicolet to the IBM. Currently, one option is available. This option utilizes Vu-Point, available from S-Cubed (a Division of Maxwell Laboratories, Inc.). Vu-Point offers additional features, such as graphics, data manipulation, and FFT analysis, in addition to data transfer.

2.4 Convert V/t Data to P/t Data. The purpose of this option is to reformat the file(s) created in the previous option for use in the data analysis portion of the program and convert the voltage data to pressure data. The conversion from voltage to pressure is based on a calibration curve which is a second-degree polynominal. In this option, either the gage information file is accessed to obtain the conversion factors, or the user enters the values directly.

2.5 Analyze P/t Data (FFT, etc.). This option allows the user to modify the pressure-time data as desired (for example, the removal of an acoustic wave due to chamber oscillations). At the present time, it is intended that this feature will be accomplished through the use of commercial software. Vu-Point by S-Cubed (see option 3) can be used to perform a wide variety of data manipulations. Other programs which may be considered are ASYSANT or ASYST from Macmillian Software Company.

2.6 Enter Firing/Reduction Data. Information pertaining to a specific firing is entered using this option. Essentially, the required information is the mass and initial temperature of both the igniter and propellant together with the desired type of data analysis—burn rate, surface area, interrupted burner, or synthetic. For the surface area or synthetic analysis, the user must provide the necessary burn rate information via $r = bP^n$ burn rate laws or in a tabular form of burn rate vs. pressure.

2.7 Smooth/Differentiate P/t Data. Final preparation of the data for the subsequent analysis is performed using this option. The first step is to reduce the size of the data file. At BRL, Nicolet 2090 or 4094 model oscilloscopes are used for data acquisition. Use of these model oscilloscopes can result in excess of 16,000 data points being recorded. However, the majority of the recorded data points correspond to pressures either before ignition or after propellant burning is completed. These values are not used in the data analysis and are deleted from the data file to shorten program run times. After the file size is reduced, three additional operations are performed on the data. The first step is the removal of "outliers" or "wildpoints." Next, the data are smoothed to minimize the effects of irregularities which may be caused by such factors as transmission line noise or an unstable pressure transducer. Finally, the pressure data are differentiated to obtain dP/dt, which is used to determine information related to quickness and pressure rate rises but is not used for prediction of burning rate.

2.8 Burn Rate Analysis. Reduction of the pressure-time data from a closed chamber firing to determine the apparent linear burn rate for a propellant is accomplished using this option. The analysis is designed to accommodate homogenous, layered, and deterred propellants. Details relating to the actual computational method are provided in the following section.

2.9 Surface Area Analysis. The surface area analysis option is used to determine the amount of surface area which must be exposed and burning at a given time to support the pressure recorded in the closed chamber. In addition to the pressure-time data and propellant thermochemistry, the analysis assumes that the linear surface regression or burn rate of the propellant is known. This type of analysis is useful in the development of more progressive grain geometries and in the study of grain fracturing.

The computations performed in this analysis are identical to those of the burn rate analysis (described in the next section) except for the final step. The final step in computing the linear burn rate is given by Equation 1.

$$r = \frac{\dot{m}}{\rho^{*} A_{l}} , \qquad (1)$$

where r is the burn rate, $\dot{m}$ is the mass rate of change, ρ is the propellant density, and A_i is the grain instantaneous surface area. If r is known instead, the instantaneous grain surface area could be computed using Equation 2.

$$A_i = \frac{\dot{m}}{\rho^* r} . \tag{2}$$

2.10 Synthetic Mode Analysis. This option is the inverse of the burn rate analysis. It is used to generate a theoretical pressure-time history given the propellant burn rate.

2.11 Interrupted Chamber Analysis. The High Pressure Combustion Diagnostic facility at BRL has the capability of performing interrupted chamber or blow-out bomb firings. In these firings, a disk at one end of the chamber ruptures at a predesignated pressure. The resulting depressurization extinguishes propellant burning and ejects the propellant from the chamber. Until recently, the only analysis performed was visual inspection of the ejected grains. This option, however, allows for the reduction of the partial pressure-time data to propellant burn rate information. The analysis is identical to that of the burn rate analysis except that the expected heat loss must be provided by the user.

2.12 Prepare Output. This option simply prepares the final output from whatever analysis was performed. Aside from tabulated results, graphical output and determination of $r = bP^n$ burn rate laws are provided. At the present time, commercial software packages are being utilized to construct the appropriate graphs.

3. LAYERED AND DETERRED PROPELLANTS

One of the major purposes for the development of the BRLCB computer program is to allow for the burn rate analysis of layered and deterred propellants. A layered propellant generally consists of two distinct propellants. Figure 1 illustrates a layered propellant in a "sandwich" configuration in which one type of propellant is placed between another type. In practice, the outer propellant, A, burns at a slower rate than the inner propellant, B, and the sides of the grain which expose both propellants are inhibited so that burning proceeds from the top and bottom through the slower burning propellant to the faster burning inner core.

The intent is to "tailor" the mass generation rate not through control of the surface area, but by introducing a more rapidly burning propellant at the appropriate time. This concept for "programming" the mass generation rate is the same for deterred propellants, but, in the deterred propellant, distinct propellants are not utilized. Instead, a homogeneous propellant is immersed in a solution which results in the formation of a layer on all exposed surfaces of the grain of a continuously decreasing concentration of the solution or deterrent. As with layered propellant, this deterrent layer is designed to reduce the burning rate of the propellant. Thus, in theory, a deterred grain possesses a continuously increasing burn rate until the homogenous inner core is reached.

As indicated earlier in the paper, the current implementation in BRLCB of layered and deterred propellants is to allow for a description of the grain using up to ten homogeneous layers. Figure 2 provides an end view of a deterred single perf grain with three layers to illustrate the positioning of the layers. This description for deterred propellants is believed to be adequate since actual deterrent concentration levels in the grain are not given continuously but are provided at discrete distances into the grain.

4. THEORETICAL ANALYSIS OF CLOSED-CHAMBER COMBUSTION

A closed chamber is a rather simple device which monitors transient combustion with a single diagnostic—a wall-mounted transducer. Except for the initial conditions, this pressure-time record is the only information available to deduce an effective linear regression rate of the material confined in the chamber. Of course, predicting this regression (or burning) rate is not a new problem. A number of methods of varying levels of sophistication have been advanced over the years, as illustrated in Robbins and Horst (1976); Price and Juhasz (1977); Oberle, Juhasz, and Griffie (1987); Robbins and Lynn (1988); and references therein. Although a comprehensive review is beyond the scope of the present paper, it appears that two basic approaches have been employed. The first method derives a closed-form solution for mass remaining (or consumed) in the chamber as a function of the experimental value of pressure. The second method derives a differential equation for the rate of change of propellant mass which must be numerically integrated in time. This, of course, must be accompanied by some estimate of the time derivative of chamber pressure from the experimental data.

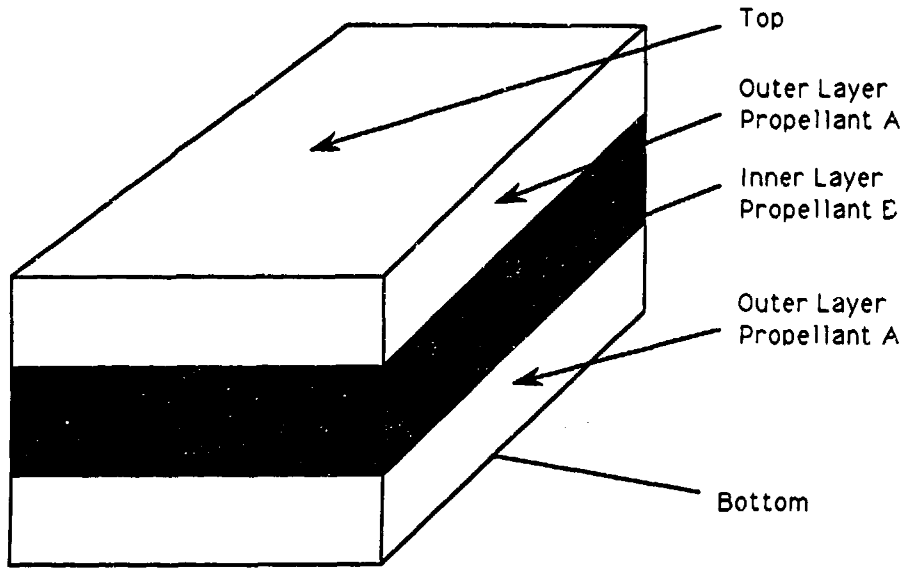

Figure 1. Layered "Sandwich" Grain.

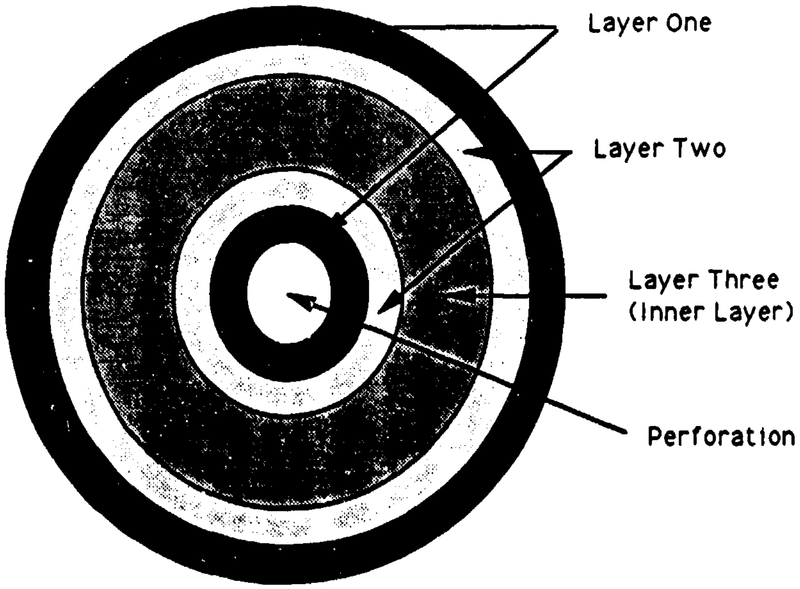

Figure 2. End View of 1-Perf Deterred Grain Described by Three Layers.

In the authors' opinion, the first method (closed form solution) is superior. The second method can be encumbered by stability and accuracy problems associated with forward time integration and also requires that the experimental pressure-time data be differentiated. With an objective to eliminate as many sources of error as possible, the present analysis will be based on a closed-form solution (first method). Although derived independently, the analysis shares the general approach first outlined by Robbins and Horst (1976).

The closed chamber analysis invokes several assumptions common to a "well-stirred reactor." Velocities within the chamber are assumed vanishingly small, and, hence, balance of momentum implies spatially uniform pressure. For consistency, kinetic energy is assumed negligible compared to stored thermal and chemical energy. Other properties are spatially invariant as the result of the "well-mixed" assumption. The eventual goal is to allow the solid material placed in the chamber to have continuously varying properties as a function of depth burned. In the present model, the material is composed of distinct layers—as illustrated in the previous section—each of which can be characterized by different properties (density, stored chemical energy, etc.). Hence, the properties of the combustion gases entering the chamber at any given time will depend upon the particular layer of material which is burning. The chamber initial condition assumes that the igniter material has been consumed, although a description of igniter combustion could easily be added in the future.

5. DERIVATION OF EQUATIONS

For a chamber of fixed volume, V_{ch}, let

P_{ch} = chamber pressure,

T_{ch} = chamber temperature,

V_{free} = chamber volume not occupied by solid material.

A co-volume equation-of-state for the gas mixture will have the form,

$$P_{ch}\,\{V_{free} - \textit{volume occupied by gas molecules}\} = R_0 T_{ch} \sum_{i=1}^{N} \{\textit{no. of moles of gas}\}. \quad (3)$$

Subscript "i" denotes distinct properties of the gases produced by combustion of the "i[th]" propellant layer. Next, define

m_{s_i} = mass of solid material "i" remaining in the chamber,

m_{cg_i} = mass of combustion gas "i" in the chamber,

m_{ig} = mass of igniter gas in the chamber,

m_a = mass of air in the chamber.

Also let

$$b = co\text{-}volume,$$

and

$$\Re = \frac{R_0}{M} ,$$

which will be subscripted in the same manner. M is the molecular weight of the gas mixture. Then, the free volume in the chamber is simply

$$V_{free} = V_{ch} - \sum_{i=1}^{N} m_{s_i}/\rho_{s_i} .$$

The equation-of-state for the gas mixture van be written as

$$P_{ch} \left\{ V_{free} - \sum_{i=1}^{N} b_{cg_i} m_{cg_i} - b_{ig} m_{ig} - b_a m_a \right\} = T_{ch} \left\{ \sum_{i=1}^{N} \Re_{cg_i} m_{cg_i} + \Re_{ig} m_{ig} + \Re_a m_a \right\} . \quad (4)$$

If $m_{s_i} (t = 0) = m_{s_i}^{o}$, and $m_{s_i} (t)$ decreases to zero as combustion of the "i[th]" layer is completed, simple mass conservation gives

$$m_{cg_i} (t) = m_{s_i}^{0} - m_{s_i} (t) . \quad (5)$$

Use of Equation 5 in Equation 4, together with the definitions

$$\alpha_i \equiv \frac{1}{\rho_{s_i}} - b_{cg_i}$$

$$K_1 \equiv V_{ch} - b_{ig}\, m_{ig} - b_a\, m_a - \sum_{i=1}^{N} b_{cg_i}\, m_{s_i}^0 ,$$

and

$$K_2 \equiv \Re_{ig}\, m_{ig} + \Re_a\, m_a + \sum_{i=1}^{N} \Re_{cg_i}\, m_{s_i}^0 ,$$

leads to

$$P_{ch} \left\{ K_1 - \sum_{i=1}^{N} m_{s_i}\, \alpha_i \right\} = T_{ch} \left\{ K_2 - \sum_{i=1}^{N} \Re_{cg_i}\, m_{s_i} \right\} . \tag{6}$$

Note that K_1 and K_2 can be computed from given information and remain constant thereafter.

If E represents total energy contained in the volume, V_{ch}, the first law of thermodynamics states that

$$E_0 = E(t) + Q_w(t) , \tag{7}$$

where $Q_w(t)$ is the cumulative heat loss from the chamber. Initial energy E_0 is simply

$$E_0 = m_{ig} e_{ig}^0 + \sum_{i=1}^{N} m_{s_i}^0\, e_{s_i}^0 , \tag{8}$$

where e^0 is the specific internal energy of the material at the "0" reference condition. Equation 8 neglects stored thermal energy in the solid material at the initial temperature. For any time greater than zero, the igniter material has been converted to gaseous products, and the total energy can be represented as

$$E(t) = \sum_{i=1}^{N} m_{s_i}\, e_{s_i}^0 + T_{ch} \left\{ m_{ig} c_{v_{ig}} + m_a c_{v_a} + \sum_{i=1}^{N} m_{cg_i}\, c_{v_{cgi}} \right\} , \tag{9}$$

where c_v is specific heat at constant volume. Making use of the mass balance in Equation 5 and defining the constant,

$$K_3 \equiv m_a c_{v_a} + m_{ig} c_{v_{ig}} + \sum_{i=1}^{N} m_{si}^0\, c_{v_{cgi}} ,$$

the energy balance in Equation 7 can be written as

$$E_0 - Q_w(t) = \sum_{i=1}^{N} m_{s_i} e^0_{s_i} + T_{ch} \left\{ K_3 - \sum_{i=1}^{N} m_{s_i} c_{v_{cs_i}} \right\} . \tag{10}$$

The analysis which follows is based on the convention that propellant layers are numbered $i = 1,2,\ldots,N$ and when layer "j" is burning ($1 \le j \le N$),

layers 1,...,j - 1 have been consumed ($m_s = 0$), and
layers j+1,...,N are unburned ($m_s = m_s^0$).

Now, define the sums

$$S_1 \equiv \sum_{i=1, i\neq j}^{N} \alpha_i m_{s_i} \qquad \text{and} \qquad C_1 \equiv K_1 - S_1$$

$$S_2 \equiv \sum_{i=1, i\neq j} \Re_{cg_i} m_{s_i} \qquad\qquad C_2 \equiv K_2 - S_2$$

$$S_3 \equiv \sum_{i=1, i\neq j} c_{v_{cg_i}} m_{s_i} \qquad\qquad C_3 \equiv K_3 - S_3$$

$$S_4 \equiv \sum_{i=1, i\neq j} e^0_{s_i} m_{s_i} \qquad\qquad C_4 \equiv E_0 - Q_w(t) - S_4 \, ,$$

which allows Equation 6 to be written as

$$P_{ch}(t) \, \{C_1 - \alpha_j m_{s_j}\} = T_{ch}(t) \, \{C_2 - \Re_{cg_j} m_{s_j}\} \tag{11}$$

and Equation 10 as

$$C_4 - e^0_{s_j} m_{s_j} = T_{ch}(t) \, \{C_3 - c_{v_{cg_j}} m_{s_j}\} \, . \tag{12}$$

Solving Equations 11 and 12 simultaneously for m_{s_j} gives

$$Q_A m^2_{s_j} + Q_B m_{s_j} + Q_C = 0 \, ,$$

which has the simple solution

$$m_{s_j} = \frac{\{-\ Q_B + \sqrt{Q_B^2 - 4Q_AQ_c}\ \}}{2Q_A} , \tag{13}$$

where

$$Q_A \equiv P_{ch}\alpha_j c_{v_{cg_j}} - \Re_{cg_j} e_{s_j}^0$$

$$Q_B \equiv e_{s_j}^0\ C_2 + \Re_{cg_j} C_4 - P_{ch}\ [\alpha_j C_3 + c_{v_{cg_j}} C_1]$$

$$Q_C \equiv P_{ch} C_1 C_3 - C_2 C_4 \ .$$

Once the solution for m_{s_j} has been determined, chamber temperature $T_{ch}(t)$ follows directly from Equation 12. Note that the value of chamber pressure at which the "jth" layer "burns out" is given by $Q_C = 0$ or

$$P_{ch}\Big|_{burnout} = \frac{C_2 C_4}{C_1 C_3} \ . \tag{14}$$

When the "jth" layer is consumed, $m_{s_j} = 0$, and the analysis automatically assumes that the "j+1" layer begins burning with the initial condition $m_{s_{j+1}} = m_{s_{j+1}}^0$. When the last or "Nth" layer has been consumed, the function $m_s(t)$ has been determined. The time derivative dm_s/dt can easily be determined by finite difference with second-order accuracy. In several checkout cases, this finite difference derivative was compared to the differential of a cubic spline and found to have the same accuracy. Given the instantaneous surface area, A_l, as a function of depth burned, the effective linear regression rate is simply

$$r = \frac{dm_s/dt}{\rho_s \cdot A_l} \ .$$

6. COMPUTER PROGRAM VALIDATION

To quantify potential truncation and/or round-off error resulting for the computer implementation of the mathematical model, results from six test cases will be presented. In addition to quantifying the error associated with the computer implementation, these test cases can also be viewed as validating the mathematical model. (Note, units for the burn rate are centimeters/second and pressure is given in megapascals).

6.1 Test Case 1. For test case 1, a synthetic pressure/time profile, generated from a known burn rate, is created using an analytic procedure provided by Robbins and Lynn (1988). Thus, the pressure/time data are exact, and the results of the burn rate analysis using BRLCB should provide a measure of the truncation/round-off error resulting from approximating the time rate of change of the propellant mass by numerical differentiation.

Results from the BRLCB burn rate analysis are given in Figure 3 on a log-log scale. As can be seen from the graph, the computed burn rate is linear with the least-squares fit to the data $r = 0.73639 * P^{1.00002}$, which is in excellent agreement with the burn rate used to generate the pressure/time data, $r = 0.73679 * P^{1.0}$. Thus, the mathematical model and its computer implementation appear to be accurate in predicting propellant burn rate from pressure/time data.

To quantify truncation and round-off error, the percent difference between the BRLCB computed burn rate and the burn rate used to generate the pressure/time profile is presented in Figure 4. From the figure, the percent difference starts at about -.044% and decreases, with a linear trend, to around -.055%. The decrease in the percent difference may be reflective of propagation error being added to the local truncation error. However, the small magnitude of the initial and final percent difference would appear to indicate that truncation and round-off error will not significantly affect results predicted by BRLCB.

Based upon the comparison of the burn rates computed by BRLCB and those used to generate the synthetic/analytic pressure/time data, it appears that the mathematical model and computer implementation of BRLCB is accurate in predicting propellant burn rate from closed chamber pressure/time data. In addition, the truncation/round-off error due to numerically approximating the time rate of change of the propellant mass is within acceptable limits.

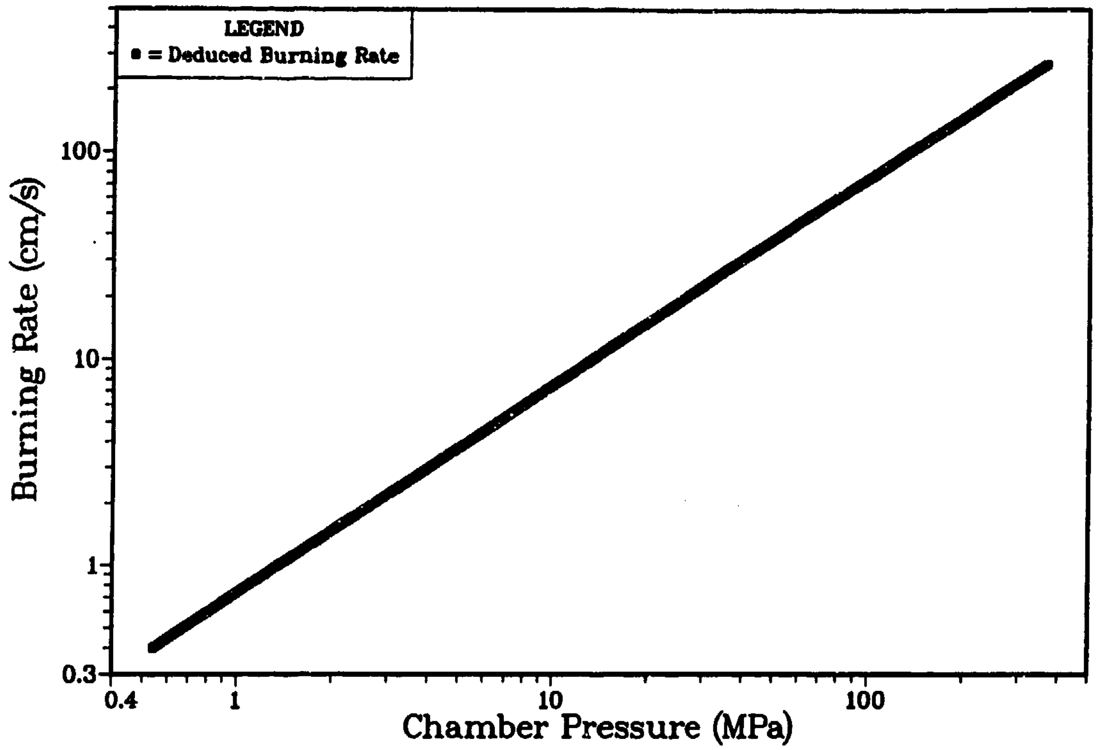

Figure 3. BRLCB Computed Burn Rate, Test Case 1.

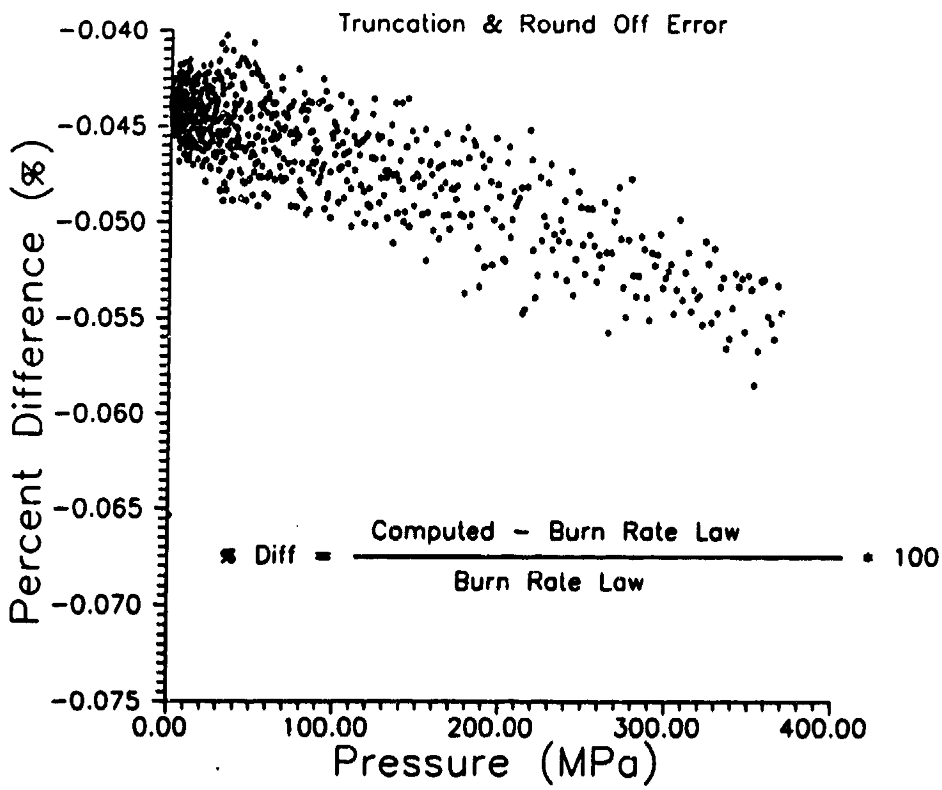

Figure 4. Percent Difference, BRLCB Burn Rate vs. Actual Rate.

It is the numerical approximation of the time rate of change of the propellant mass which is the greatest potential source of error in the computer analysis. The first test case demonstrated that this is not a significant error, less than 0.055%, when the derivative of the mass change corresponds to a burn rate representative of typical propellants. However, it is of interest to determine if the program is sufficiently "robust" to accurately predict propellant burn rate when the time rate of change of the propellant mass is much steeper. Unfortunately, the synthetic/analytic technique used to generate the data of test case 1 requires a burn rate law exponent of exactly 1.0. Therefore, to simulate a high burn rate case, pressure/time data were generated using the interior ballistic code IBHVG2 (Anderson and Fickie 1987) to simulate a closed chamber experiment. Unlike the Robbins-Lynn technique of test case 1, IBHVG2 uses numerical approximations in its computations. These numerical approximations can introduce inaccuracies in the data which are input to the BRLCB analysis. Thus, the second test case is similar to the first test case and is used to determine the effect of using data generated by IBHVG2. In order to minimize potential error resulting from calculations involving the grain geometry, a spherical propellant grain is utilized.

6.2 <u>Test Case 2</u>. For test case 2, the burn rate computed by BRLCB is given in Figure 5.

As in Figure 3, the burn rate shown in Figure 5 is linear except for the last several points. The least-squares linear fit to the data, except for the last several points, is virtually identical to the burn rate used to generate the pressure/time data in IBHVG2 ($r = 0.145 * P^{0.95}$), the exponent being 0.95 accurate to three decimal places. This represents a 0.09% maximum percent difference with the burn rate used in IBHVG2. Subsequent analysis indicates that the non-linear increase exhibited in the last several points of Figure 5 is an artifact of the IBHVG2 calculation. Thus, except for possibly the last several data points, using IBHVG2 generated pressure/time data as input to BRLCB does not introduce significant numerical inaccuracies in the BRLCB results.

6.3 <u>Test Case 3</u>. The parameters for this test case are the same as in test case 2, except that the propellant burn rate used in the IBHVG2 calculation is increased to $r = 23.7815 * P^{2.3}$ to produce a extremely sharp rise in the propellent mass change time derivative. Results of the BRLCB calculation are presented in Figure 6.

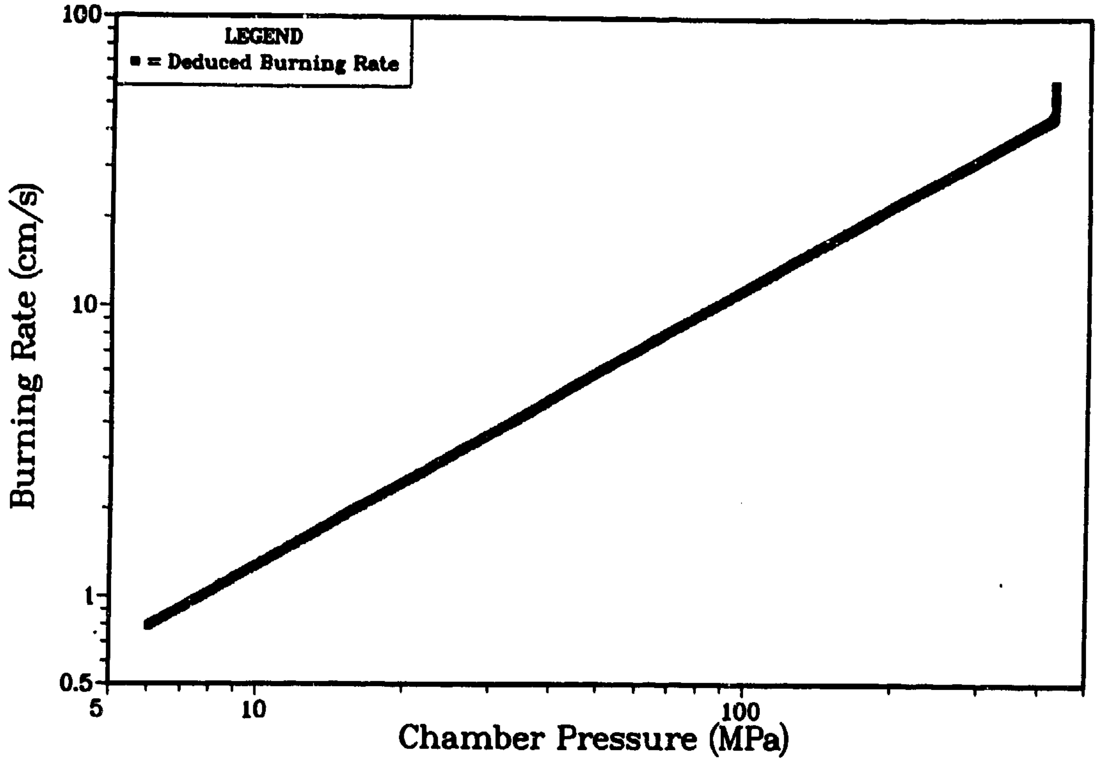

Figure 5. BRLCB Computed Burn Rate, Test Case 2.

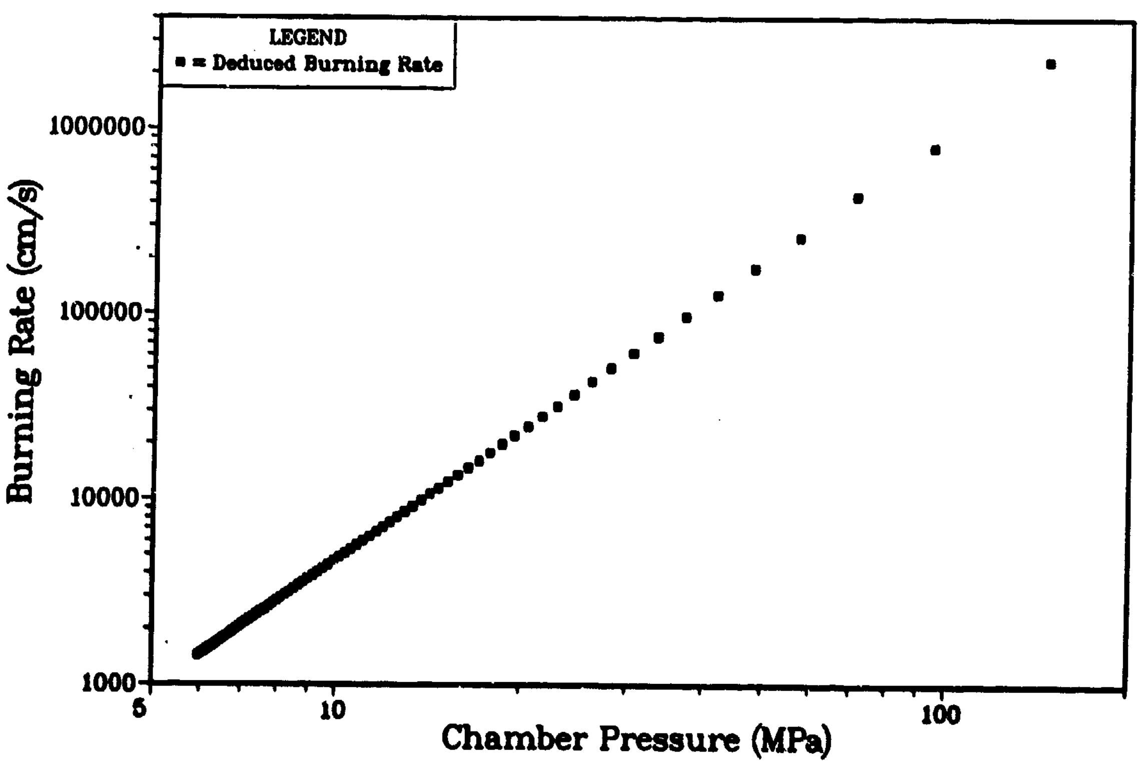

Figure 6. BRLCB Computed Burn Rate, Test Case 3.

The computed burn rate, Figure 6, is again linear with a burn rate index (exponent in the burn rate law) of 2.3, accurate to three significant digits. The maximum percent difference with the burn rate used in IBHVG2 is 0.4%. Although the 0.4% difference for case 3 and the 0.09% difference for case 2 represents an increase over the percent difference for case 1, a portion of the increase may be due to truncation and round-off errors in the IBHVG2 calculation since numerical routines are used in IBHVG2. Thus, considering the magnitude of the burn rate index, 2,3, and potential truncation/round-off error in IBHVG2, the authors believe that the BRLCB calculation is accurately reproducing the burn rate even for extremely rapid burning propellants.

Test cases 1 through 3 demonstrates BRLCB's capability to analyze situations which consist of homogenous grains. However, when dealing with layered or deterred grains, there will be transitions for a layer of one homogeneous propellant to a second layer with different propellant properties. In general, this transition will not occur exactly at the end of a time step in the calculation. Thus, there could be points in the calculations where the code deals with discontinuities in the propellant properties. To investigate the effect that these discontinuities could have on the BRLCB calculation, test cases for a layered grain with a jump discontinuity in the burn rates of the two layers and for a deterred grain are analyzed.

6.4 Test Case 4. This test case is for a layered grain with a jump discontinuity in the burn rates of the two layers. The outer layer burn rate is $r = 0.4 * P^{0.7}$, and the inner layer rate is $r = 0.2 * P^{0.95}$.

The results of the BRLCB calculations are shown in Figure 7. Again, as in case 2, the last several computed values are in error as a result of the data supplied by IBHVG2. Clearly evident are the burn rates for the two layers. Both computed burn rate indexes, 0.7 for layer 1 and 0.95 for layer 2, are accurate to three decimal places as in test case 2. The transition between the two layers takes place over two time steps (due to IBHVG2) and appears, at least for this test case, to present no difficulty to the program.

6.5 Test Case 5. The intent in this test case is to simulate a deterred grain. Unfortunately, due to the inability of IBHVG2 to simulate more than two distinct layers, the deterred grain will consist of two layers with the burn rates of the layers adjusted so that there

is no jump discontinuity in the rates at the transition from layer 1 to layer 2. In this case, the burn rate for layer 1 is $r = 1.0 * P^{0.35}$ and for layer 2, $r = 0.066 * P^{0.95}$. Results of the BRLCB calculations are shown in Figure 8.

Again linear burn rates for the distinct layers are evident with the burn rate indexes exhibiting the same degree of accuracy as in the previous case. Also, the code experiences no difficulty in the transition region between the layers.

To summarize, the results of test cases 1 through 5 indicate that BRLCB can accurately reproduce propellant burn rate information given closed chamber pressure/time profiles. Maximum truncation/round-off error is less than 0.055% for synthetic/analytic data and in the range of 0.09% to 0.4%, depending on propellant burn rate, for data from IBHVG2. Finally, the program appears to be capable of correctly analyzing the data in the transition region between propellant layers where discontinuities occur in the propellant properties.

The authors feel that these five test cases validate the mathematical model and computer implementation for performing the burn rate analysis of options 8 and 11 (see Table 1) of the BRLCB program. Although it will not be presented in this paper, the synthetic mode analysis, option 10, has also been validated. The final analysis mode, option 9, surface area analysis, is addressed in the final test case.

6.6 Test Case 6. As in test case 1, the pressure/time data from the synthetic/analytic technique due to Robbins and Lynn (1988) are used. However, in this analysis the burn rate is known and the instantaneous surface area is sought (see Equation 2). Generally, the surface area information is present in normalized form, obtained by taking the ratio of the instantaneous surface area to the original surface area. Figure 9 presents this ratio as a function of the propellant mass fraction burnt as computed by the BRLCB program. Figure 10 gives the same ratio computed analytically for a single perf grain as a function of mass fraction burned.

A comparison of the graphs in Figures 9 and 10 show that the curves overlay each other, validating option 9.

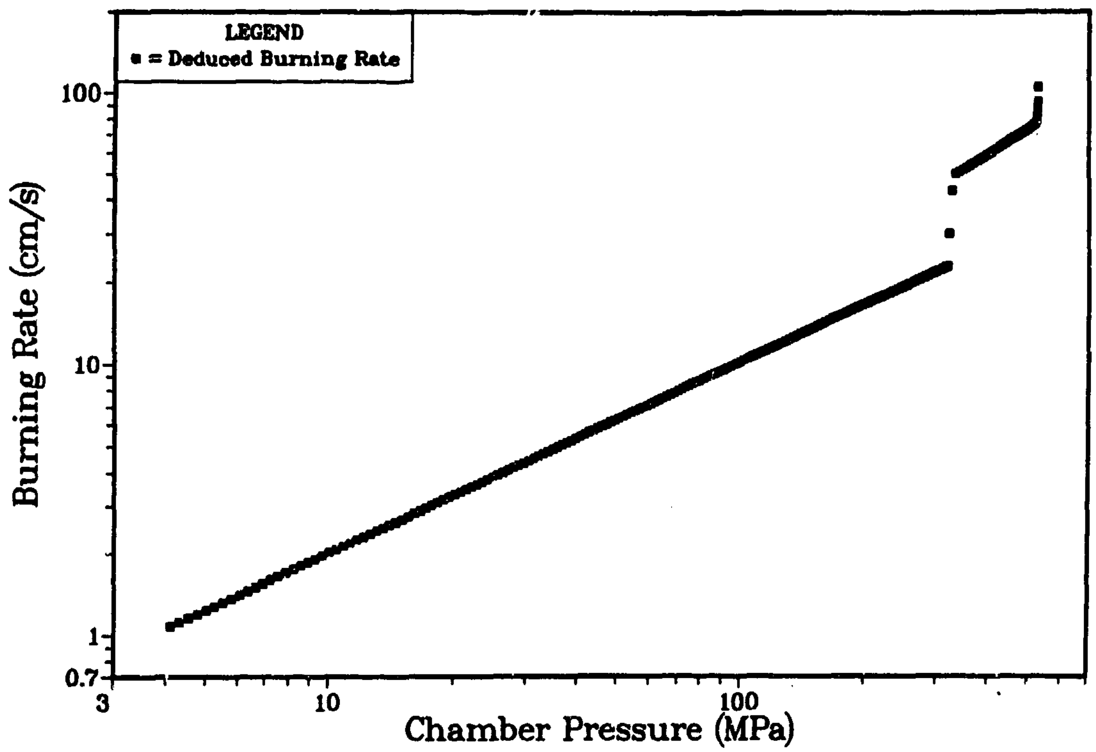

Figure 7. BRLCB Computed Burn Rate, Test Case 4.

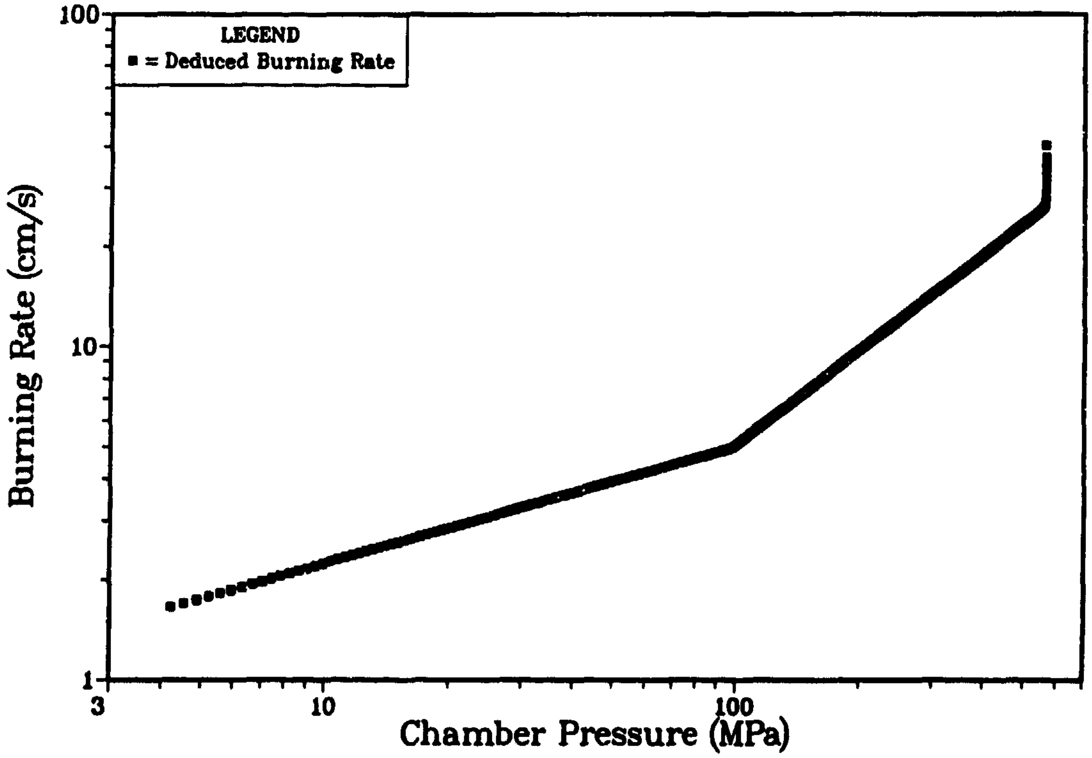

Figure 8. BRLCB Computed Burn Rate, Test Case 5.

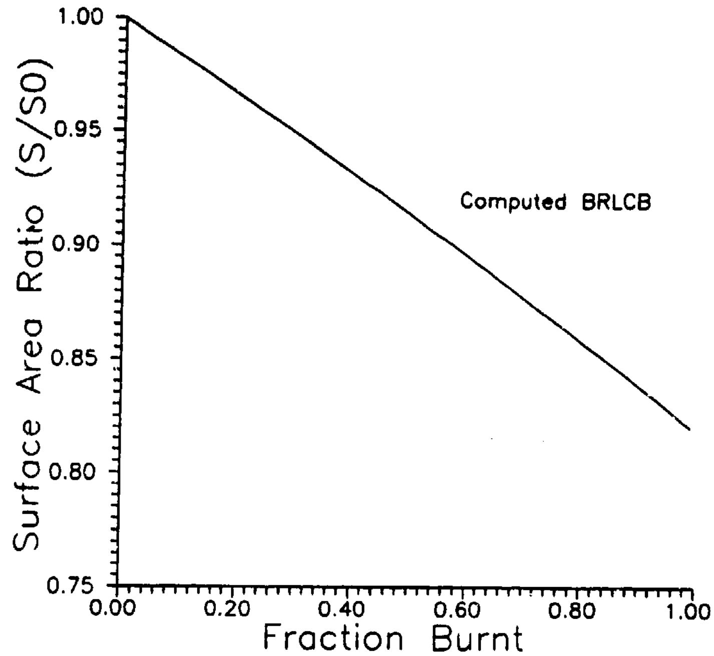

Figure 9. BRLCB Computed Surface Area Ratio, Test Case 6.

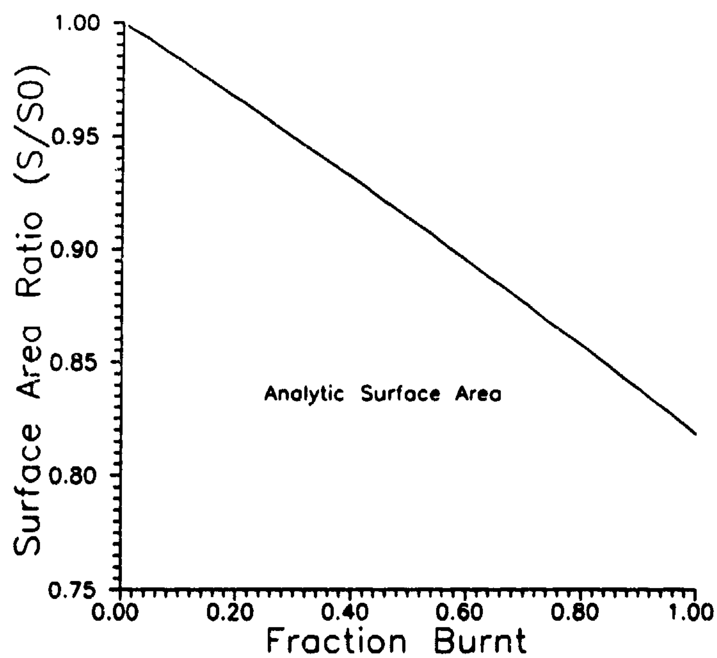

Figure 10. Analytic Surface Area Ratio, Test Case 6.

7. FUTURE PLANS

Although the authors believe that the current mathematical model for BRLCB and its implementation provide an excellent tool for analyzing experimental closed chamber data, two areas of possible improvement will be addressed. The first involves the assumptions concerning energy losses. The second is the representation of deterred grains as consisting of up to ten layers of homogeneous material.

In the current model, the difference between the theoretical maximum pressure and the observed maximum pressure is a measure of the energy losses. The incremental energy loss is then applied to the analysis in direct proportion to the pressure rise. That is, the portion of the total energy loss assumed at any step in the analysis is the same as the ratio of the current pressure to the maximum observed pressure. This results in the energy losses being linearly and uniformly apportioned throughout the analysis. The authors believe that the assumption of a linear distribution of the energy losses may not be correct. Experiments aimed at determining the actual energy loss distribution are planned with incorporation of the results into the current model.

Since deterrent concentrations are provided at discrete distances into the propellant grain, the authors believe that the representation of deterred grains by up to ten homogeneous layers should be sufficient to provide an adequate analysis. However, in order to determine the validity of this assumption, equations, assuming the propellant properties are known in a continuous manner will be derived and implemented via a computer program, and, the results will be compared with the current model. Even if no significant differences are observed, incorporating continuous propellant properties will simplify and expand the model by eliminating the need for special form functions for the deterred and layered grains and by allowing layered and deterred analysis for any grain form function.

8. CONCLUSIONS

BRLCB is a PC-based computer program implementing a mathematical model designed to perform all necessary closed chamber data analysis. In this report, the basic features of the program together with the supporting theory of the mathematical model have been presented.

In addition, results of various test cases indicate that BRLCB can accurately reproduce propellant burn rate information or instantaneous surface area given closed chamber pressure/time profiles. Results indicate that maximum truncation/round-off error is less than 0.055% for synthetic/analytic data and in the range of 0.09% to 0.4% for data obtained using the interior ballistic code IBHVG2. The program also exhibits no difficulties in analyzing data in the transition region between propellant layers where discontinuities occur in the propellant properties.

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